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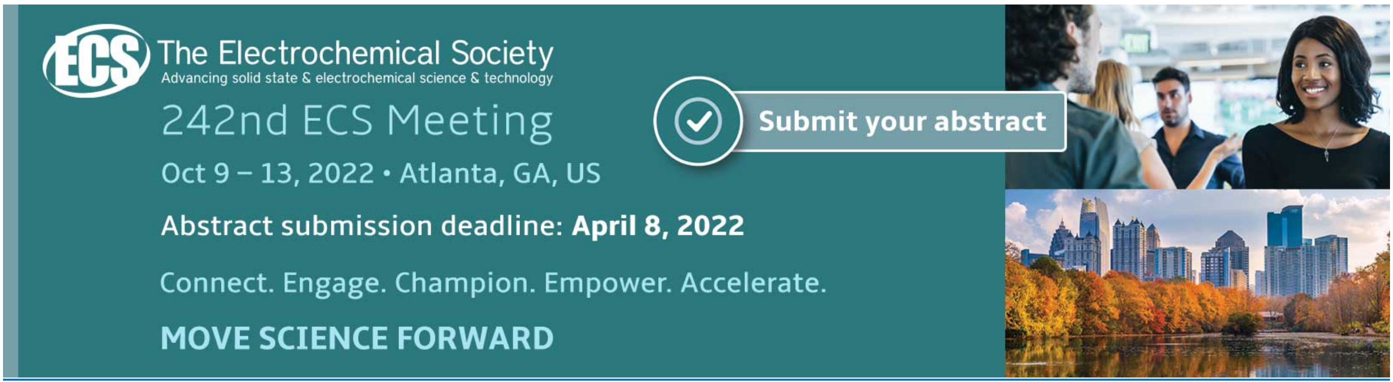

Testing fundamental cosmological assumptions with *Euclid*

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Abstract. The forthcoming *Euclid* survey will be able to map the large scale structure with unprecedented precision, with the aim of tightly constraining the standard cosmological model and its most common extensions. The great sensitivity of *Euclid* can however also be exploited to test our most fundamental assumptions at the basis of the cosmological investigation. In this work we present two recent results of the Euclid Consortium, where forecast *Euclid* products are used alongside data from other surveys to constrain violation of the distance duality relation and time evolution in the fine-structure constant. We show how *Euclid* will significantly contribute in constraining these effects, both connected with the presence of new physics beyond the standard cosmological model.

1. Introduction

After the latest data release from the Planck Collaboration [1], which provided the state of the art constraints from cosmic microwave background (CMB) observations, the standard cosmological model ΛCDM is still the most efficient model to explain cosmological observation. However, the increase in sensitivity brought by *Planck* has highlighted how the value of some parameters inferred from CMB observations is now in tension with independent measurements (see e.g. [2] for a review).

In the present decade, new cosmological surveys will try to shed light on such tensions, investigating the possibility that these are due to new physics or to unknown systematic effects. In particular, large-scale structures (LSS) surveys will be crucial to put to test models alternative to ΛCDM and assess the possibilities for these to ease the tensions.

Among the upcoming LSS surveys, the ESA *Euclid* satellite will have as one of its primary goals to constrain dark energy (DE) and modified gravity (MG) models, thanks to the tomographic reconstruction of the dark matter (DM) distribution in the Universe, possible thanks to its galaxy clustering and weak lensing observations [3]. These models are however simple extensions of the ΛCDM model, and rely on most of the same assumptions that are at the base of it.

In this work we focus instead on the capability of *Euclid* to put to test some of these fundamental assumptions, and we quantify its constraining power on deviations from the standard distance duality relation (DDR) and on the possible time variation in the fine-structure constant.

2. Breaking fundamental assumptions in cosmology

In this work, we focus on two possible observable signatures that arise from the violation of basic assumptions contained in the standard cosmological model: a deviation from the DDR and a time variation in the fine-structure constant α. We sketch here the theoretical modelling and the analysis performed; a more detailed derivation of the analysis and of possible physical mechanisms responsible for departures from the standard paradigm can be found in [4, 5].

2.1. Departures from the distance duality relation

The ΛCDM model relies on the assumption that gravity is described by a metric theory, where photons move along null geodesics and with the number of photons being conserved. Within such a framework, the Etherington relation [6], also known as the DDR, implies that the luminosity distance, $d_{\rm L}(z)$, is related to the angular-diameter distance, $d_{\rm A}(z)$, as

$$d_{\rm L}(z) = (1+z)^2 d_{\rm A}(z)\,. \tag{1}$$

From a theoretical point of view, models violating the DDR through a violation of photon number conservation would affect the luminosity distance measures but not the determinations of the angular-diameter distance. This means that probes of the latter (BAO) can be combined with supernova surveys, which provide information on $d_{\rm L}$, to constrain deviations from photon number conservation.

Deviations from the standard DDR are commonly encoded in a function $\eta(z)$, defined as

$$\eta(z) = \frac{d_{\rm L}(z)}{d_{\rm A}(z)(1+z)^2} = (1+z)^{\epsilon(z)}. \tag{2}$$

In this work, we rely mainly on a constant parameterization, assuming $\epsilon(z) = \epsilon_0$, but, as we are also interested in a possible redshift dependence of such departures, we take one step further and also consider a simple binning of this function in two redshift bins, that is $\epsilon(z) = \epsilon_0$ for $z < z_*$ and $\epsilon(z) = \epsilon_1$ for $z \geq z_*$, where $z_* = 0.9$ is a transition redshift.

2.2. Time variation of the fine-structure constant

When deviations from ΛCDM are explored, it is common to substitute the cosmological constant with a scalar field (ϕ), driving the accelerated phase of the expansion, whose equation of state is commonly parameterized as $w_\phi(z) = w_0 + w_a z/(1+z)$ [7, 8].

While dynamical scalar fields in an effective four-dimensional field theory are naturally expected to couple to the rest of the theory, unless a still unknown symmetry is postulated to suppress these couplings, the common approach is to assume that the scalar field is minimally coupled. Here, we drop this assumption, and allow the scalar field to be coupled, through a coupling parameter ζ, to the electromagnetic sector. It can be shown [5, 9], that such a coupling would imply a time variation in the fine-structure constant α, and that one can explicitly relate the evolution of α to that of the DE scalar field:

$$\frac{\Delta\alpha}{\alpha}(z) = \pm\zeta \int_0^z \sqrt{3\Omega_\phi(z')\,|1 + w_\phi(z')|}\frac{\mathrm{d}z'}{1+z'}\,. \tag{3}$$

where Ω_ϕ is the fractional energy density for the scalar field DE component, and the plus and minus sign refer to canonical and phantom scalar fields respectively [10].

While Eq. (3) is interesting at cosmological times, one can also predict the current drift rate of the value of α, which can easily be found to be

$$D \equiv \left(\frac{\dot{\alpha}}{\alpha}\right)_0 = \mp\zeta H_0\sqrt{3\Omega_{\phi0}|1 + w_0|}\,, \tag{4}$$

again with the minus and plus signs corresponding respectively to the canonical and phantom cases.

3. Constraints on violations of the distance duality relation

As it is clear from Eq. (2), in order to constrain the ϵ_i parameters, we need observations of both the luminosity and angular distances. We therefore explore the constraining power that can be achieved combining supernova observations (SnIa) from the Legacy Survey of Space and Time (LSST), performed by the Vera C. Rubin Observatory [11], with the Baryon Acoustic Oscillations (BAO) measurements of *Euclid*, obtained following the approach of [12]. In addition to this we also include BAO observations from DESI [13], and the possible supernova survey of the *Euclid* satellite DESIRE [3, 14].

Our results, obtained comparing theoretical predictions for different values of the free parameters, are summarized in Fig. 1. It is possible to notice the significant improvement in constraining power that will be brought by future surveys, whose combination improves the currently available constraints (shown in red) of a factor ≈ 6. The right panel shows instead the constrained evolution of the $\eta(z)$ function of Eq. (2), highlighting how future surveys will be able to constrain this effect also in a more general scenario.

4. Constraints on the time variation in the fine-structure constant

In order to constrain the time variation in α, a crucial observable is the direct measurement of α that can be performed at cosmological redshifts observing absorption lines of distant quasars. Here, we focus on the future measurements that will be provided by the high-resolution ultra-stable spectrograph HIRES [15], that will be installed at the Extremely Large Telescope (ELT),

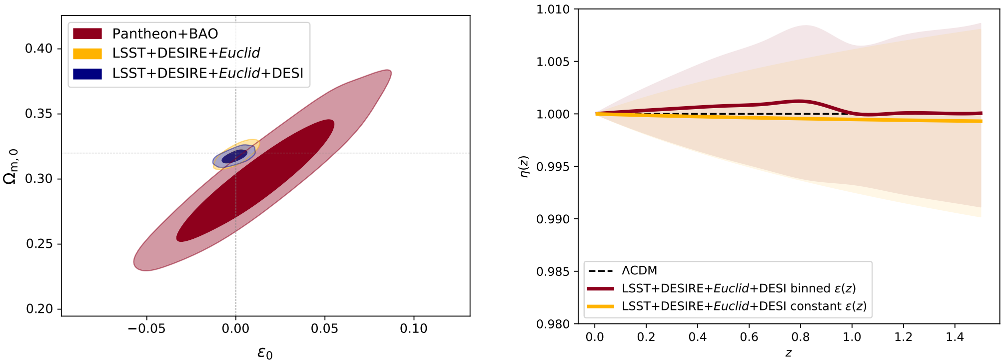

Figure 1. *Left panel:* 68% and 95% confidence level contours on $\Omega_{\mathrm{m},0}$ and ϵ_0 obtained combining currently available measurements for DDR violation (red), combining upcoming LSST and *Euclid* surveys (yellow), and by adding DESI to the latter combination (blue), in the constant $\epsilon(z)$ case. *Right panel:* reconstruction of the constrained mean trend and 68% confidence level region of the DDR deviation function $\eta(z)$, in both the constant (yellow) and binned (red) cases.

and we combine it with the most stringent current bound on the drift D of α, provided by [16]. As it can be expected from Eq. (3) and Eq. (4), even with extremely precise measurements of α it would be extremely difficult to tightly constrain the coupling ζ as it will be degenerate with the DE parameters entering Ω_ϕ and w_ϕ. For this reason, synergies between the ELT and *Euclid* will be crucial; the expected precision on the DE parameter of *Euclid* will allow to break such degeneracies and to tightly constrain the parameters ruling the time variation in α. Here, we assume that the direct effect of variations in α on *Euclid*'s observables is negligible. While this is indeed expected to be small, a more detailed investigation is needed to further explore its relevance.

We show in Fig. 2 the results obtained combining *Euclid* constraints on cosmological parameters [12] with the future α measurements described above, obtained with twofiducial cosmologies: ΛCDM (left panel) and a cosmology that deviates from the standard one and produces a time variation in α (right panel). As it can be seen in both panels, the inclusion of *Euclid* in the analysis is crucial to break the degeneracies between ζ and the DE parameters.

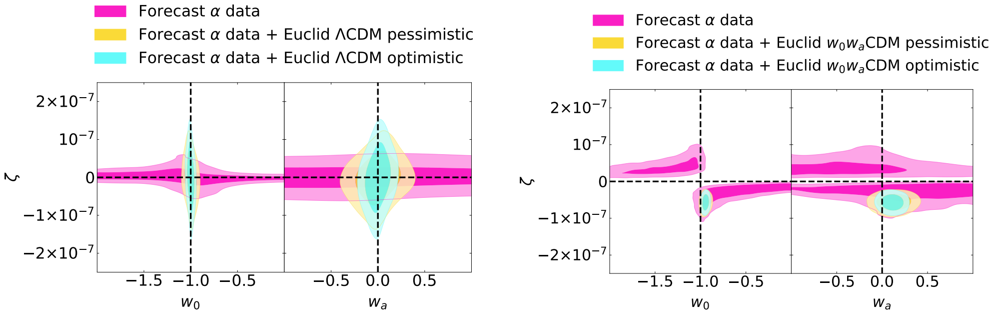

Figure 2. 68% and 95% confidence level contours in the ζ–w_0 and ζ–w_a plane if a ΛCDM (left) and non-standard (right) fiducial cosmologies. The pink contours show the constraints achievable by α measurements alone, while yellow and blue contours highlight the impact of *Euclid* in, respectively, the pessimistic and optimistic cases described in [12].

5. Discussion

In this work, we have shown how dropping assumptions that lie at the basis of the cosmological standard model gives rise to effects that can be constrained with the observations of upcoming cosmological surveys. The main result we stress here is that the Euclid satellite will provide crucial observations to test fundamental assumptions, and the possible synergies between this facility and other contemporary cosmological survey will improve significantly the constraining power on the effects we considered in this work. In particular we found that the combination of *Euclid*, DESI and LSST will allow to improve by a factor ≈ 6 the current constraints on violation of the DDR, and that *Euclid* sensitivity to DE parameters will be crucial to break the degeneracies between these and the possible coupling ζ of DE scalar fields to the electromagnetic sector.

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